RF/Photonic Receiver System based on Fragmented Aperture Antennas and Rotman Lenses

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***Abstract*— A low size weight and power (SWaP) photonic receiver system, which combines a custom-designed fragmented aperture antenna, custom Rotman lens, and commercial off the shelf (COTS) photonic devices is presented. Signal direction detection is successfully demonstrated using the photonic receiver system. The receiver system can determine angle of incidence with 5 ° of resolution, and the frequency of an incoming signal.**

Keywords—photonics, electronic warfare, RF, aperture array, Rotman, radar

I. INTRODUCTION

A low SWaP system capable of discerning the angle of incidence of received radio frequency signals is presented. Future SWaP reduction can be achieved via component integration into a photonic integrated circuit (PIC). The antenna can be used in beam steering applications for transmission or sensing. This system can be used to determine the angle of incidence passively, without active scanning or antenna steering. Removing scanning requirements further reduces system complexity and weight. The antenna used is a 1 x 8 fragmented aperture design, with optimized characteristics. Radar range is determined conventionally by processing returned signals. If received signals are digitized, then a filter can de-convolve received signals for sensing or rebroadcast. With a system such as the one presented modified signals may be easily returned. By stacking similar subsystems, both azimuthal and inclination range finding can be enabled.

The backend of the antenna array feeds to a Rotman lens which acts as passive distribution to beamform without the need for active electronics. A system model was produced, and calculations were performed for gain, noise figure, and dynamic range. The custom antenna and Rotman lens were designed, modeled, fabricated, and then measured in a laboratory. Next, the antenna and Rotman lens were connected with COTS photonics into a novel receiver system concept. The system was measured from RF-in to RF-out across a range of parameters to characterize beam width, angle of arrival, and gain at each port. Other receiver system configurations were also demonstrated. The photonic circuit operates on the RF input to show a change in output when the input beam angle of incidence changes. This was tested using a horn antenna with RF source at 18 GHz with a power of 10 dBm. EOSpace X-cut $LiNbO_3$ modulators were used for source laser modulation of the RF input.

Section II provides a description of both the design and operating principles, an RF link budget, and a discussion of possible modifications to the design. Section III includes results and measurements of the system design specifications. Section IV contains concluding remarks, a summarization of the design, and future work.

II. EXPERIMENTAL SETUP AND SYSTEM CHARACTERIZATION

A. Receiver System

The setup for a photonic receiver is shown in Fig. 1. A fragmented aperture antenna [1, 2] is connected to the Rotman lens, having eight input and output ports. Each radiator element on the antenna connects to a unique input on the lens via SMA. For testing purposes, six of the output elements were terminated with resistors, with the remaining two outputs connected to the photonic backend. Terminators and connected antenna elements were alternately moved during testing for direction finding characterization.

The photonic backend has two identical channels in this set up. The RF input is amplified and fed into a phase modulator. These Mach-Zehnder modulators have a 1554 nm laser providing the carrier signal. The input waveguide is split into two paths of identical length fibers and recombined at the output of the phase modulator. An impressed electric field, modulated here by the amplified RF signal received by the combined antenna and lens, applies a phase change to one path inside the modulator. When the two signals are recombined at the modulator output, they interfere destructively or constructively based upon the applied phase shift [3 – 5].

The signal then enters a photodetector, and the detected intensity is modulated by the phase shift. The resulting electronic signal output of the modulator is then amplified before being read by the oscilloscope. One envisioned deployable system would employ digital processing and computer control in order to read out and interpret the received signal and then act on output signals at this point in the chain.

The RF link budget estimate is presented in Table I. The free-space path loss (FSPL) is calculated using Friis transmission equation,

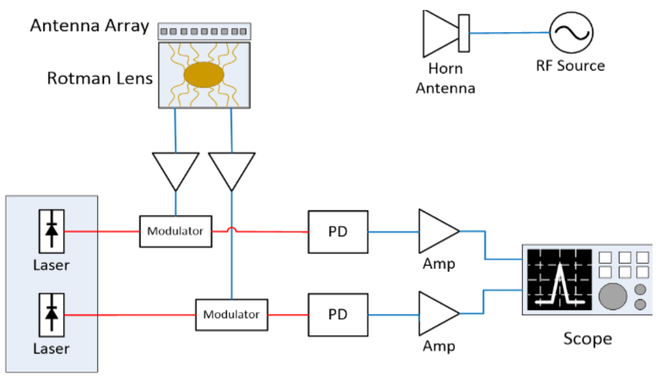

Fig. 1. Block diagram of system demonstration including remote signal source, antennas, photonic and RF components.

TABLE I. RF LINK CALCULATION

RF Link Budget Estimate		
Stage	***Level***	***Level***
Power at signal generator	-	10 dBm
Cable loss to antenna	-1 dBm	9
TX Antenna gain (dBi)	18	27
Path loss (15 ft free air)	-70.75	-43.75
RX Antenna gain	14.8	-28.95
Rotman lens gain	-	-28.95
Cable loss	-1	-29.95
Amplifier gain	12.36	-42.31
RF photonics link gain	-9	-51.31
Amp gain	12.36	-38.95

$$FSPL = 20log_{10}d + 20log_{10}f + 20log_{10}\frac{4\pi}{c} - G_t - G_r \quad (1)$$

with d as a distance of 4.75 m (15 ft), f as a frequency of 18 GHz, c equivalent to the speed of light, and G_R and G_t as the gain of the receiver and transmitter, the FSPL is calculated to be -70.75 dB.

B. Antenna

The antenna was designed using a fragmented aperture design technique implemented by GTRI [1, 2]. This approach uses a pixelated mask and genetic algorithms to optimize for specific performance metrics. Thousands of simulations utilizing random mutations are completed and scored against the desired antenna characteristics until a suitable candidate is found. Specifically, this antenna was scored to maximize h-pol gain from 6 to 18 GHz. The antenna was designed as a 1 x 8 array. Owing to the small array size, further optimizations were performed to account for edge effects and other phenomena unique to this type of antenna. Fig. 2 depicts the designed fragmented aperture arrangement used in the system. Fragmented aperture antennas can be cheaply and quickly fabricated using standard circuit board fab processes.

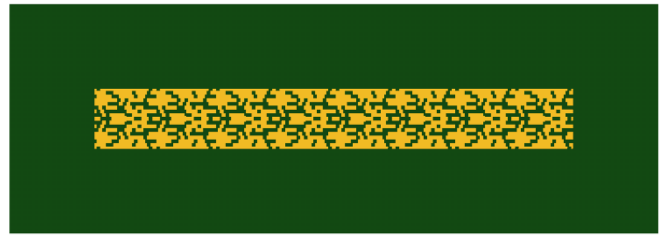

Fig. 2. The final layout of the fragmented aperture array antenna, which uses 8 identical segments.

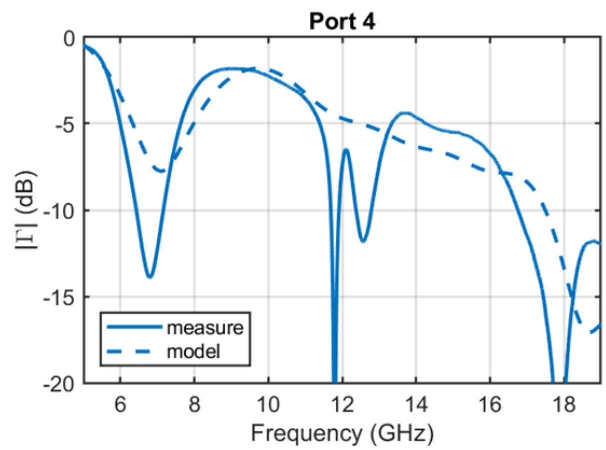

Fig. 3 – Reflection coefficient of fragmented aperture antenna as modeled and measured from 6 to 18 GHz.

The 1 x 8 array was designed specifically to allow steering by introducing unique phasing at each element, achieved through implementation of the Rotman lens.

Once the optimized antenna was fabricated, it was tested in GTRI's compact range. A reflection coefficient measurement was taken for each of the 8 ports and compared to the modeled results. Antenna performance simulation and measurement comparison for port 4, representative of an interior array element are presented in Fig. 3. All of the elements have similar performance to this one, with slightly degraded performance at elements 1 and 8, owing to edge effects. The additional optimization previously mentioned successfully mitigated some of these effects.

C. Rotman Lens

The Rotman lens is a true time delay structure where the scan angle is determined by the input port locations. The geometric theory was developed in [6]; constant phase shifts are achieved at antenna ports.

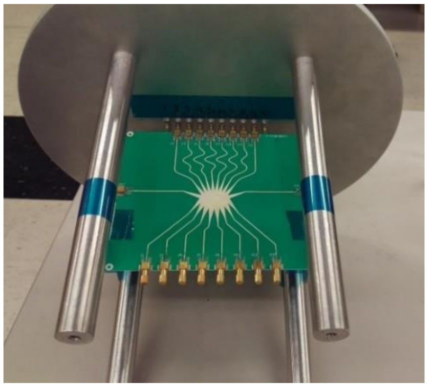

Fig. 4. Rotman lens printed on PCB connected to a positioner antenna mount flange.

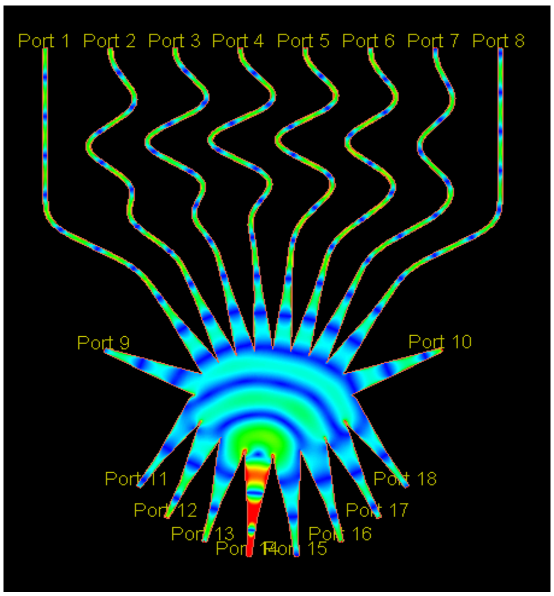

Fig. 5. Keysight Momentum simulated current flow for the Rotman lens demonstrating the signal-binning and routing phenomena.

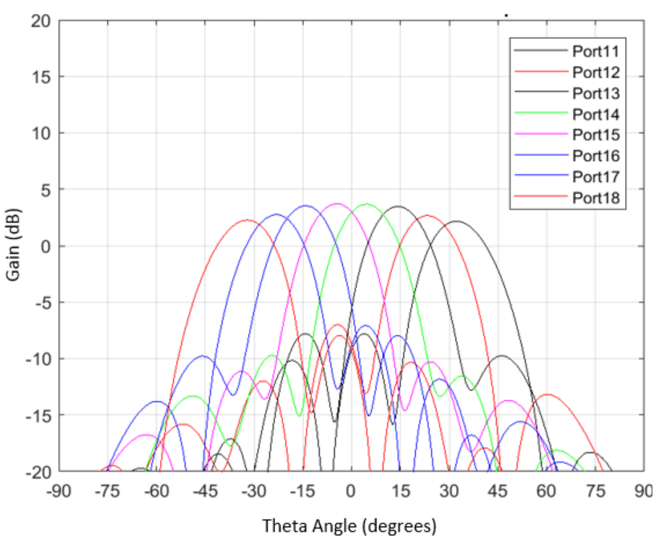

Fig. 6. The simulated E-plane radiation patterns for all beam ports of the Rotman lens show angle separation.

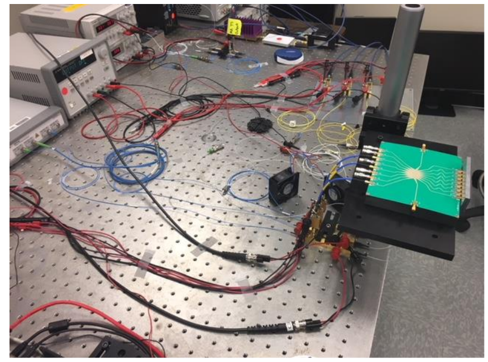

Fig. 7. Photonic components and source as connected on the optical bench are envisioned to be reduced to a single PIC in future iterations.

The Rotman lens, shown in Fig. 4, was designed for 6 – 18 GHz using GTRI's custom design software, and was then verified using both Keysight's Momentum and Ansys's High Frequency Structure Simulator, shown in Fig. 5. The simulated E-plane radiation patterns for all beam ports are shown in Fig. 6.

D. *Photonic Backend*

An Aligent Technologies N7714A laser source at 1554 nm is used as input to the optical side of the system. Phase-maintaining fiber is used to connect components. COTS components are used for the following: EOSPACE amplitude modulators are used in conjunction with MITEQ LCA-0618 amplifiers and DSC30S photodiodes. This connected photonic and RF circuit is shown in Fig. 7. The RF output is read by a digital oscilloscope with an FFT function applied. The receiver will receive 18 GHz broadcast from an RF source and AS-48461 horn antenna. In the absence of a phase shift, the photodetectors are presented with light of constant intensity, and output DC current. Since the phase is modulated at a frequency of 18 GHz, which is easily distinguishable, the change in intensity at the output of the modulators occurs at the same rate. Consequently, since the photodetector output current is proportional to intensity, an 18 GHz signal, or other received frequency, is detected by the oscilloscope.

III. Measurment Results and Discussion

Measurement results for the photonic receiver system are presented. The goal of the experiment is to measure the Rotman lens output as a function of RF source incidence angle. The topology of the angle measurement is shown in Fig. 8. Measurements were taken on 2 of the 8 Rotman output channels simultaneously. The complete receiver system was tested in a laboratory setting. An RF source turned to 18 GHz was connected to the broadcast horn antenna, transmitting with a power of 10 dBm from a distance of 15 feet. The antenna and lens were placed on the platform and rotated.

Given the small size of the antenna array compared to the 15 foot separation distance from the RF source (well within the Fraunhoffer region), the received signal can be approximated with an 18 GHz plane wave. Therefore, a marked peak in the signal will be observed from each output channel based upon the angle of rotation of the antenna and lens angle of rotation.

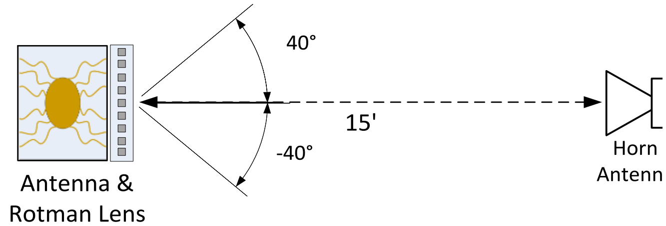

Fig. 8. The antenna array and Rotman lens receiver are placed on a gimbal with angle measurements as the broadcasting horn antenna is moved within this space.

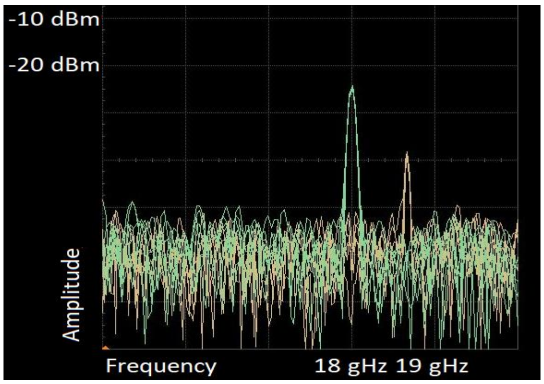

Fig 9. Measurements of the system output are shown as processed by FFT. The two peaks show angle of incidence as received by different antenna apertures. The channels are offset for easier viewing.

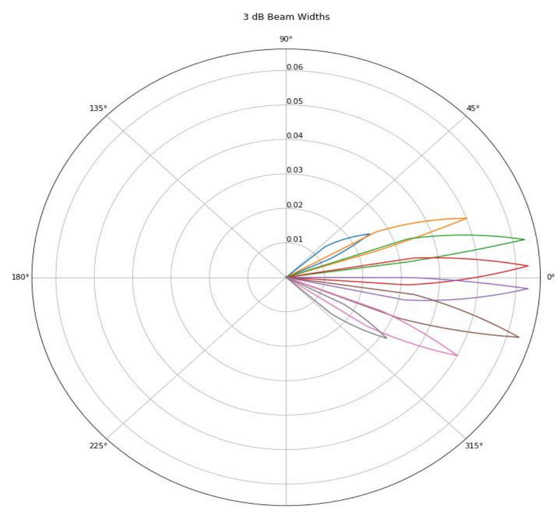

Fig. 10. Portions of measured amplitude versus angle for all eight output channels overlaid. For each channel, only the portion exceeding -3 dB from peak is illustrated.

The electrical measurement output of the system is shown in Fig. 9, where the lens is rotated to achieve a peak in one receive channel. The level of an adjacent channel is pictured in yellow. Despite appearances, both channels are receiving the same 18 GHz signal. The signal shown in yellow in Fig. 9 is intentionally offset to clarify the picture.

The repeated angle measurements resulted in the measurement shown in the polar plot of Fig. 10, wherein a broadcaster's position can be determined, as received by the different port outputs of the Rotman lens. The estimated accuracy currently is estimated to be ±2 °, in part due to the protractor used, which can be easily improved. The antenna element beam width per channel mean is 15 °, with 60 dBm noise level.

This simple design is intended to provide a proof of concept. More sophisticated designs are possible, including a switch or multiplexer in the optical paths, allowing the inclusion of multiple photonic receiver systems with separate antennas. This allows for a system capable of simultaneous broadcast and receive duties, potentially with intermediate RF circuits and processing.

IV. Summary and Conclusions

A simple RF electronic-photonic system has been presented which is able to determine azimuth of a transmitting object at distance. The individual elements of the system including antenna, Rotman lens, and photonic COTS components have been detailed. The results of an experiment measuring incident RF radiation angle was performed and measurements were presented.

Millimeter-wave broadcast signals suffer high atmospheric attenuation and therefore require high gain antennas, which by correlation, will also have a narrow beam-width. Narrow beam-width antennas benefit from and likely require high directional continuous steering. The antenna array presented here provides a solution for this wavelength regime and related applications. The antenna array used in conjunction with a Rotman lens enable simultaneous receiving and re-broadcast of signal. Furthermore this array design is extendable by expansion. When installed over a curved surface, the array pattern can be further extended and useful aircraft protective scenarios. A cross-pattern variation of this antenna or planar array should enable both azimuth and inclination determination. Distance calculation via triangulation of received peaks and determination of locational data within 3-D space are future efforts. An expanded design may require a Rotman lens with additional ports, or use of an additional lens. Finally, system integration of components into a single PIC will drastically improve miniaturization.

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